Andor Bauernhuber[1], Tamás Markovits[2]

THERMAL ANALYSIS OF LASER TRANSMISSION JOINING PROCESS APPLYING PMMA PLASTIC AND STEEL

Abstract: The application of laser transmission joining in the case of dissimilar materials is a novel and active field for research. Nevertheless the mechanism and the processes of joining are not fully explained yet. This research– based on the previous results of the authors – was aimed at investigating the joining of poly(methyl methacrylate) plastic and structural steel. In order to better understand the phenomenon during joining, the characteristic temperature of the samples were measured and the effect of irradiation time and laser settings on the sample temperature and on the joining mechanism were described.

Key words: PMMA, steel, laser, thermal analysis

1. Introduction

The spreading application of plastics necessitates the research on new technologies, which allow to process and so to join these materials as well. Laser transmission joining is a well known and used technology in industry, which enables the fast and efficient joining of plastics by exploiting the advantages of laser technology (KAGAN V. 2002). Transmission joining can be applied in case of different materials as well, as several researches report, facilitating the simultaneous use of different materials' advantages (ACHERJEE B.2011, ROESNER A. 2011, JUNG K.W. 2013). However, joining metals and plastics raises several difficulties due

[1] Assistant lecturer, Budapest University of Technology and Economics, Department of Automobiles and Vehicle Manufacturing, andor.bauernhuber@gjt.bme.hu
[2] Associate professor, Budapest University of Technology and Economics, Department of Automobiles and Vehicle Manufacturing, tamas.markovits@gjt.bme.hu

to their very different material properties, like strength, melting temperature or thermal expansion (FARAZILA Y. 2012). In order to make this new joining technology competitive with widely used technologies, like adhesives and mechanical fastening, the difficulties have to be solved and the process of joining have to be clarified. To achieve this goal in the case of a post-moulding technology, the knowledge of temperature and temperature distribution in the material and at the interface of the bonding is essential. According to this suggestion, the aim of this work is to measure the temperature during the laser joining process of PMMA plastic and steel, and to investigate the effect of laser settings and material partners on the temperature present during joining.

2. Experiments

Materials used in the experiments were S235 structural steel and poly(methyl methacrylate) (Acriplex PMMA-XT) sheet, the steel had a pin geometry. The thickness of the sheet was 2 mm, the size 15x15mm, the geometry of the steel pin sample and the experimental setup can be seen in figure 1. The laser beam source was a LASAG SLS 200 type, pulse mode Nd:YAG laser with a maximum pulse power of $P_{max}=5.5\ kW$ and with an average power of $P_a=220\ W$. The power distribution of the laser beam was Gaussian ($TEM_{0,0}$). The temperature was measured with a K-type thermocouple with a wire diameter of 0.25 mm, which was welded on the lateral surface of the steel pin, close to the edge at the head surface. The temperature distribution of the surface was observed by a thermovision camera type FLIR A325sc.

Transparent absorbent laser joining enables us to prepare overlapped bonds; the upper partner has to be transparent for the laser beam, while the lower part has to absorb the radiation. In this case the upper PMMA material has a transparency of about 92% at the applied laser wavelength (MARKOVITS T. 2013). Thus, the heated lower material transmits heat back to the upper partner, which melts, and by applying an appropriate compressive force between the joining partners, after cooling down, the joint is created.

To understand the effect of plastic sheet on the heating process, three different situations were used: in the situation ’A’, the steel pin was radiated directly at its face side, where the focal spot of the laser beam coincided with the steel pin surface. The diameter of the spot was Ø5 mm in each case. In situation ‘B’, the PMMA plastic sheet was placed 0.5 mm above the steel pin, without the pin touching it. In this case, because of the high transparency of the PMMA, the laser beam passes the plastic and will be absorbed on the metal partner, where heat is generated. In situation ‘C’, the steel pin is pushed into the plastic sheet with a clamping force of 3.2 N during laser radiation. The heated face surface transfers heat back to the plastic, which softens and finally melts. As a result of the clamping force, the pin penetrates into the molten plastic, and after cooling down, the joint is created.

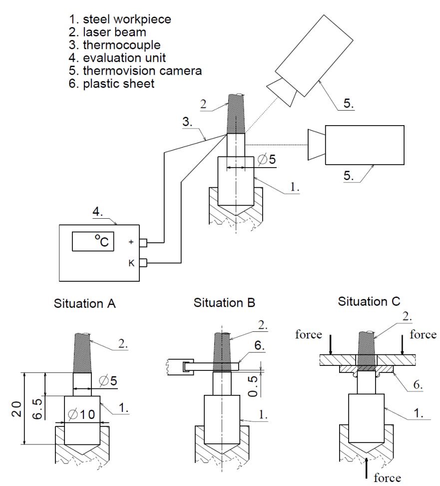

Fig. 1. Schematic view of experimental setup in (b) Situation A; (c) Situation B; (d) Situation C.

Three different laser settings were used in the experiments, to investigate the effect of beam parameters on the thermal process. The settings are listed in Table 1, each setting was used in all three situations, each experiment was repeated 3 times.

Table 1. Used laser settings

	Average power (W)	Irradiation time (s)	Pulse frequency (Hz)	Pulse time (ms)	Pulse energy (J)
Setting 1	200	4	100	0,5	2
Setting 2	200	4	5	9,9	40
Setting 3	200	7	100	0,5	2

In each case *4.75 l/min* argon shielding gas was applied. The pins were manufactured by turning, the average surface roughness of the steel pins on the lateral surface was altered between *0.8 µm* and *1.4 µm*. Roughness values were measured by a Mitutoyo Surftest 301 surface roughness tester. Before the experiment the steel pins were cleaned with acetone.

3. Results

The results of temperature measurement by thermocouple can be seen in Figure 1: the typical temperature curves present during heating are plotted in the three different settings in situation A. The temperature reaches its maximum value at the end of the laser radiation, and after that, the temperature decreases to room temperature. In line with the expectations, the irradiation time influences the maximum value of the curves: the longer the irradiation time, the higher the maximum temperature. By comparing the curves of setting 1 and 2, the effect on the heating rate and the maximum temperature can be seen: the setting with lower frequency but higher pulse energy increases the heating rate and consequently, the maximum temperature as well.

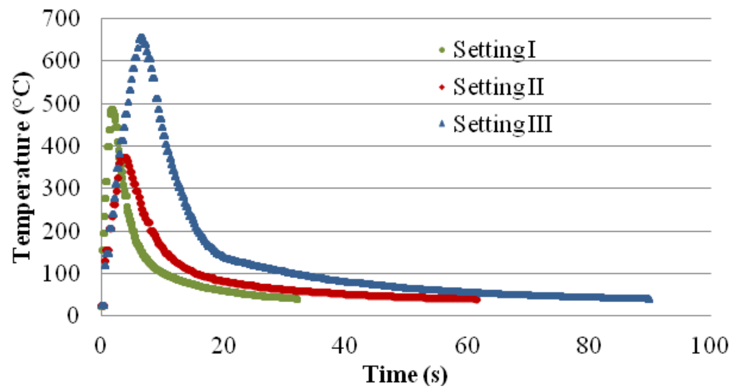

Fig. 2. Charactesistic temperature curves in situation A at different laser settings, measured by thermocouple

In Figure 3 the measured maximum temperatures are illustrated in the case of the 3 different settings and situations. It can be seen, that the PMMA sheet does not cause notable changes in the temperature of the pin: the highly transparent plastic transmits the laser beam, which is absorbed by the metal surface. However, the values at situation B are consequently higher, than at situation A: it is presumable, that the laser radiation is scattered on the polymer material, and after leaving the sheet, the radiation can heat the thermocouple wire directly, nevertheless the exact explanation needs further investigation. If using setting II and III the surface reaches a very high temperature, and the face side of the steel partially melts as well. In this case the PMMA sheet melts and slightly decomposes as a result of heat radiation, without touching the steel, as shown in Figure 4. When using situation C, the temperature decreases significantly; the steel pin transmits heat back to the plastic during its penetration, which melts and partially degrades. The heat removal caused by the plastic decreases the temperature of the steel. The signs of polymer degradation are the arising bubbles at the plastic surface, which are the decomposition products of PMMA material (KASHIWAGI T. 1982), the bubble formation is illustrated in Figure 4. These bubbles reduce the transparency of the plastic which also contributes to the lower temperatures of the steel.

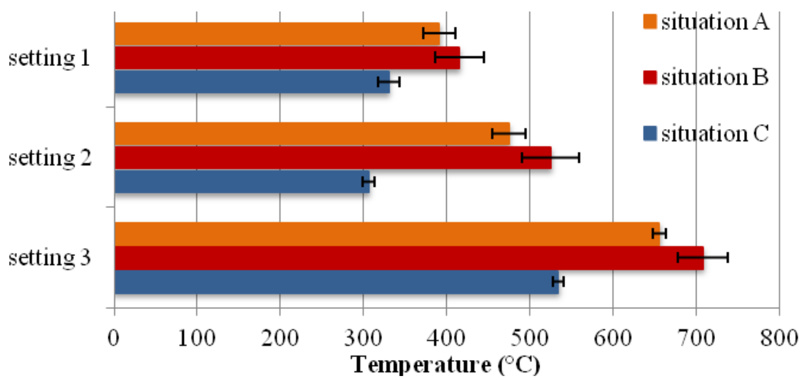

Fig. 3. Maximal temperatures at different laser settings and situations

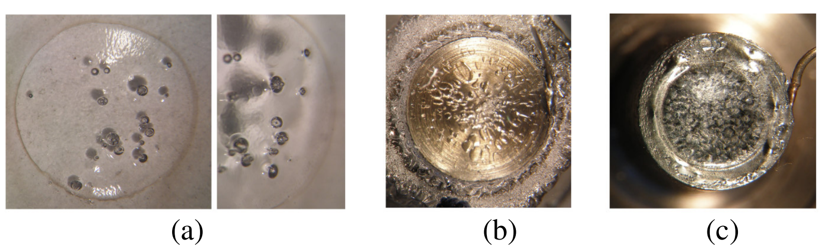

Fig. 4. Degraded PMMA in situation B at setting 3 (a), face surface of the pin in situation C at setting 1 (b) and in situation A at setting 2 (c),

The pictures of the infrared camera provide images of the heat distribution on the surface. In Figure 5 the heat distribution on the lateral surface of a pin in situation A, at setting I are shown: the pictures 1 to 4 show the process of heating, in picture 4 the pin reaches its maximum temperature. In the 5th picture, the pin starts to cool down.

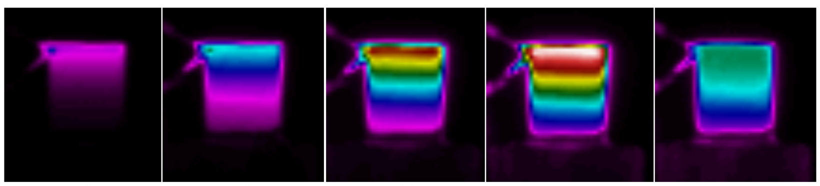

Fig. 5. Temperature time sequences on the lateral surface of the pin in setting I.

As Figure 5 shows, the isotherms on the lateral surface are nearly horizontal and symmetric, and are moving downwards on the surface during heating. This means that the temperature on the lateral surface is not influenced by the horizontal position, but is only dependent on the time and the vertical position.

The heat distributions of the face surface at situation A and setting I are shown in Figure 6 the same way as in Figure 5.

The face surface heats up in line with the Gaussian distribution of the laser beam: the middle of the surface heats up at fastest, the edge and the midpoint temperature equalizes only at the end of the heating process. The plastic material in the middle has to tolerate a longer-term, higher-temperature heating, which can explain the more intensive bubble formation in the middle of the plastic sheet, as illustrated in Figure 4.

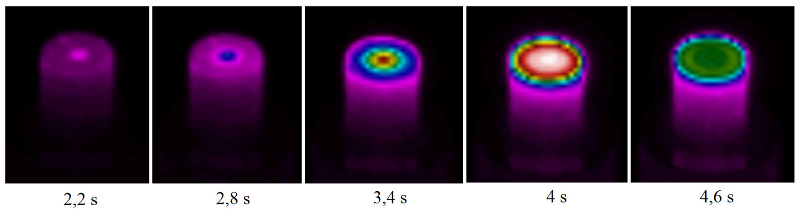

Fig. 6. Temperature time sequences on the face surface of the pin in setting I.

In Figure 7, the temperature distribution of the cross section is shown in the same way as before: the distributions back up the results already illustrated by Figure 6: near the middle of the surface the material heats up to a higher temperature, in line with the Gaussian power distribution of the laser beam, however, the temperature difference partially equalizes moving towards the bulk material.

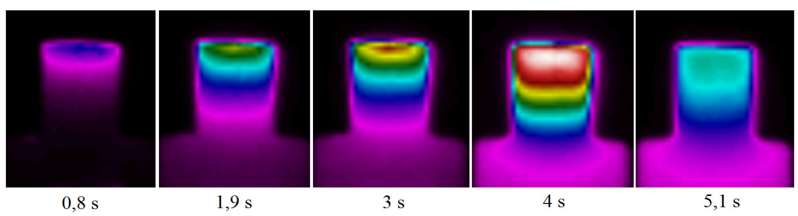

Fig. 7. Temperature time sequences on the cross section of the pin in setting I.

Figure 8 illustrates the process of temperature increase in the middle of the face surface in the case of settings I and II, using the infrared camera. We can see the difference in the nature of heating: when using low pulse frequency and high pulse energy, each pulse appears separately in the temperature diagram. Therefore, while setting I results in a continuous and consistent increase in the temperature, setting II causes a pulsating thermal growth for both the steel and the plastic material.

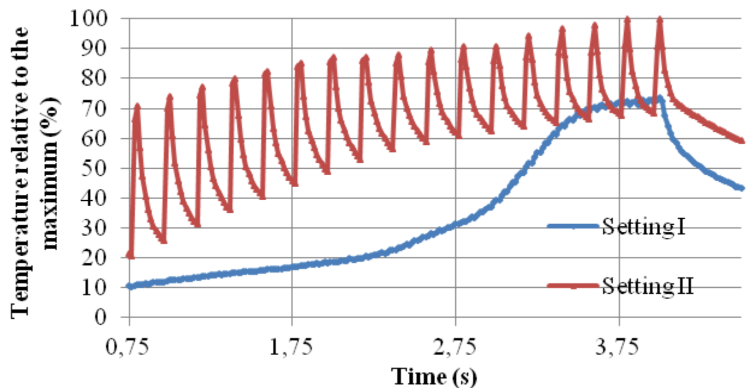

Fig. 8. Temperature curves of the midpoint on the face surface made with thermovision camera

4. Conclusions

The main conclusions drawn from the measurements described above are as follows:

- The value of maximum temperature and the rate of heating is influenced by the feed out of laser beam: high frequency and low energy pulses cause lower temperature and heating rate, while low frequency and high energy pulses result in higher temperature and heating rate.
- The temperature of the steel pin is reduced significantly by pushing it into the PMMA sheet: the heat needed to melt and partly decompose the polymer and the deteriorating transparency of the material caused by bubble formation results in lower temperatures
- The temperature distribution on the lateral surface of the pin is only dependent from the vertical position and time, but independent from horizontal position.

- The temperature distribution on the face surface of the pin is in line with the Gaussian power distribution of the laser beam; this phenomenon may be responsible for the more intensive decomposition and bubble formation in the middle part of the joining as well.
- Low frequency and high energy pulses results in a pulsating temperature of the surface and thus in a pulsating thermal growth of both materials.

5. Acknowledgement

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